



**Atacama  
Large  
Millimeter  
Array**

## **ALMA Commissioning and Science Verification Plan**

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## Change Record

Version	Date	Affected Section(s)	Change Request #	Reason/Initiation/Remarks
A	2004-02-28			Initial version
B	2004-09-03	All		Major redraft incorporating comments from R. Lucas, D .Emerson and M. Holdaway. New material on science verification.

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## 1 Description

### 1.1 Purpose

This document provides an overview of the commissioning and science verification phase of the ALMA project. It describes the scope of the activity, its relation to systems integration and operations, and an outline of commissioning activities, concentrating on the period up to Early Science (Q4 2007). Staffing, resources and support required from Operations, Systems Integration and other IPTs are also considered briefly.

### 1.2 Scope

The purpose of the **Commissioning and Science Verification** (CSV) activity is to test and optimize the elements of the ALMA system (e.g. an antenna, new correlator mode, receiver or software component) and to ensure that it meets the scientific requirements. The CSV phase starts when the mode or component is handed over by Systems Integration and ends with acceptance on behalf of the ALMA operation.


The principal outputs are:

- operational procedures and documentation for operation of ALMA as a science facility, including end-to-end data management.;
- reports documenting as-built performance, exceptions, recommendations for improvement and test data..

Commissioning and Science Verification are carried out by the same team, but are differentiated as follows:

**Commissioning** covers initial testing, interaction with SI and other construction IPTs to identify and resolve faults, optimization, training of Operations staff and documentation.

**Science Verification** (SV) is part of the activity of the commissioning team. It is done to verify and document the performance of a particular observing mode for an outside observer. It is a continuing and incremental activity, as new modes will be added continually. It tests the end-to-end system, from proposal submission to final science, with the involvement of outside users. **Demonstration science** is a

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part of the SV process. This document is primarily concerned with the verification of modes for Early Science, but the policies proposed have continuing application.

Proposal management, except for the special case of science verification, is not a CSV activity.

This document provides an overview of commissioning and science verification in Chile. It does not cover activities at the ATF, except to make recommendations about training of the CSV team.

## 2 Related Documents and Drawings

### 2.1 References

ALMA-00.00.00.00-002-H-PLA	ALMA Operations Plan
ALMA-10.04.00.00-001-A-PLA	ALMA Project Plan
ALMA-90.02.00.00-004-A-SPE	First Science Configurations
VLT-PLA-ESO-10000-0937	Very Large Telescope Commissioning Plan
	VLT Science Verification Policy and Procedures

### 2.2 Abbreviations and Acronyms

CSV	Commissioning and Science Verification
SV	Science Verification
WVR	Water vapour radiometer

### 2.3 Glossary


### 2.4 Related Interface Control Drawings

## 3 Commissioning for Early Science

### 3.1 Location

The CSV team will be located at the OSF, with significant participation from specialists located elsewhere. Work at the AOS is not anticipated except under special circumstances.

### 3.2 Equipment available

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The assumptions of this plan are that receivers for the following bands will be available when the antennas are handed over for commissioning:

3	84 - 119 GHz (3mm)
6	211 - 275 GHz (1.3 mm)
7	275 - 370 GHz (0.9mm)
9	602 - 720 GHz (0.5mm)

In addition, water vapour radiometers are assumed to be mounted on all antennas.

It is assumed that all of the ALMA antennas will be used for interferometric operation and that total-power operation will eventually be supported on a subset of four of these. The requirement for early science is that interferometric operation is supported on 6 antennas and that one may be used for total power.

The implications of the use of the Japanese 12m antennas for total-power operation are outside the scope of this document.

A limited number of correlator modes will be supported initially, based on those tested at the ATF with some modification based on scientific priorities and equipment availability. The default modes are as follows:


Bandwidth	Single polarization	Dual polarization	Full polarization
2 GHz	256	128	64
128 MHz	2048	1024	512
31.25 MHz	8192	4096	2048

Note that the ALMA correlator will support some modes (e.g. 4-bit) not available at the ATF.

Further details, as well as the requirements for back-end, correlator, computer hardware and software vary over the commissioning programme, and are outlined below.

### 3.3 Initial antenna configurations

Initial commissioning will be done with the first antennas in a close-packed configuration in order to keep baselines short and minimize atmospheric phase errors. The first 3 antennas will form the innermost triangle of the proposed Early Science Configuration. Antenna 4 will initially be positioned close to the first 3, and will then be moved out to a distance ~200m to allow initial evaluation of atmospheric phase errors. Antennas 5 and 6 will complete one of the outer triangles of the Early Science Array. Antennas 7 and 8 will

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be a distances ~1km from the centre of the array. Very limited reconfiguration will occur during early commissioning.

### 3.4 Commissioning phases

The early CSV activity in Chile falls naturally into four phases, leading up to Early Science . These are: activities at the OSF, single antenna, single-baseline interferometer and the Early Science Arrays (3 – 8 antennas). In addition, there are preparatory activities at the prototype interferometer in Socorro. The current dates are assumed to be:

Single-baseline interferometer at ATF	Q4 2004
Antenna 1 at OSF	Q4 2005
Antenna 1 at AOS (start single-antenna commissioning)	Q1 2006
Antenna 2 at AOS (start single-baseline interferometry)	
Antenna 3 at AOS (start compact configuration commissioning)	Q3 2006
Early Science	Q4 2007

Thereafter, there will be ongoing CSV tasks leading up to full science operations in Q1 2012.

### 3.5 Commissioning and Science Operations

It is assumed that dedicated commissioning activities will be interleaved with science operations from 2007, and that both will be scheduled in relatively long periods (>1 week), as described in the Operations Plan. At some point when 8-12 antennas have been commissioned, it may become feasible to use a test subarray for commissioning in parallel with science operations, particularly for the introduction of new antennas into the array.


## 4 Ongoing activities

Throughout the commissioning and verification, the CSV team will devise and accumulate software scripts and procedures for the ALMA operation, test procedures and data, reference observations and reduction scripts. The aim is to maintain complete as-built documentation for the commissioned modes for operations and commissioning staff as well as users. Extensive use will be made of the archive, both astronomical and monitor data.

## 5 Commissioning tests required before Early Science

### 5.1 Prototype Interferometer



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It is important that the CSV team gains experience with the components of the ALMA system before moving to Chile, so they should participate in tests with the prototype interferometer in Socorro. Although many of the components (including the software) are prototypes, this is sufficiently similar to the final system that significant time will be saved during commissioning in Chile. Activities could include:

- Basic interferometer operation (at Band 3?)
- Tests of the prototype water-vapour radiometers
- Initial calibrator survey

## 5.2 OSF Tests

The CSV team will also participate in test and evaluation of the antennas at the OSF, again with the primary aim of gaining experience prior to operation at the AOS. Specific activities are:

- Pointing tests with the optical telescope
- Holography
- Antenna motion tests

## 5.3 Single-antenna commissioning

The aim of the commissioning process for the first antenna is to verify that the individual antenna and receivers meet their specifications for continuum observations.

### **Equipment available:**

#### Antenna 1

Nutator (Note: if this is not available, then some alternative switching device will be required for continuum radiometry. An alternative method for pointing experiments would be to use line sources, which would require the full back-end and correlator).

Optical pointing telescope

Receivers (at least one band, preferably all four)

Back-end to include IF total-power detectors

Hardware and software to allow single-antenna operation from OSF

An outline of the test programme is as follows:

### **5.3.1 Basic operation of antenna and receivers**

- Band 3
- Higher frequencies in turn

### **5.3.2 Focus and collimation**

- Measure best focus by offsetting subreflector and maximizing signal.
- Check focus stability



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- Measure dependence of focus and collimation on elevation and temperature

#### 5.3.3 Surface accuracy

- There are no plans at present to measure the surface of a single antenna at AOS, but phase-retrieval holography could be considered.

#### 5.3.4 Pointing calibration

- Note: this assumes continuum radiometry, hence the requirement for the nutator.
- Develop initial pointing model based on the initial model derived at the OSF with the optical telescope. Initially, use Band 3 continuum. **Note: there would be considerable value in having an optical telescope available at the AOS for use in parallel with radiometric pointing tests, for the first and second antennas.**
- Check dependence of pointing model coefficients on environment (solar loading, temperature as measured by sensors, tiltmeters, .....).
- Collimation offsets for all bands. Variations and stability.
- Test metrology equipment supplied by antenna manufacturer and evaluate the need for additional measurements and incorporation into the antenna control system.
- Verify blind pointing accuracy
- Verify offset pointing accuracy
- Verify step reponse; tracking stability under various wind conditions

#### 5.3.5 Primary beam

- Measure beam map, large enough to include the first few sidelobes, for all available bands.
- Test stability and dependence on elevation of main beam gain and width, sidelobe pattern and sky/ground noise.

#### 5.3.6 Gain calibration

- Perform tipping scans to characterize the atmosphere and assess changes of system noise due to varying ground pickup, receiver attitude etc.
- Observations of planets etc. as primary flux standards; flux transfer to quasars in total-power mode.
- Test amplitude calibration system (semi-transparent vane, hot/cold load) and characterize receiver gain and system noise as functions of elevation.

### 5.4 Single-baseline interferometer

Equipment available:

Antennas 1 and 2, on closely-separated pads

Front ends

WVRs

Local oscillator

Back-end

Software for analysis of single-baseline interferometer data



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#### **5.4.1 Basic operation**

- First fringes (band 3 initially; then higher frequencies).
- Check correlation efficiency by observing point sources in continuum and spectral-line modes; compare results for total-power and interferometry at low and high frequencies.
- Control of gain (programmable attenuators)

#### **5.4.2 Antenna location (delay) calibration**

[This assumes an accurate geometric and neutral atmosphere delay model]

- Measure phase slope across the band.
- Track a source in hour angle to remove phase wraps.
- Confirm using global solution using observations using a grid of sources distributed over the sky.
- Test stability.
- Test accuracy of replacement of antenna on pad..

#### **5.4.3 Pointing, focus, collimation, primary beam profile**

- Refine interferometric test procedures developed at the ATF.
- Pointing; optimize pointing patterns (5-point, Az-El, ...)
- Focus
- Collimation
- Primary beam

#### **5.4.4 Surface**

- Measure surface using interferometric holography (Band 3: sensitivity?)
- Check variations with elevation, etc. Check for consistency of derived surface errors with radiometric measurements of aperture efficiency.

#### **5.4.5 Local oscillator coherence**

- Measure common-mode phase errors
- Measure independent phase errors
- Derive calibration procedures


#### **5.4.6 Water-vapour radiometers**

- Basic functional tests.
- Compare measurements from WVRs on closely separated antennas to assess precision and reliability.
- [Note that this may require re-use of prototype WVRs if production units are not available.]

### **5.5 Close-packed Array (antennas 1 – 4)**

#### **Equipment available:**

As for single-baseline interferometry, but adding  
Antennas 3, then 4 on pads close to the initial two

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Software for antenna-based calibration and imaging

#### **5.5.1 Calibration procedures**

- Qualify calibration procedures for pointing, focus etc. initially with 3, then with 4 antennas (the procedures differ for 2, 3, and >3 antennas)

#### **5.5.2 Antenna-based complex gain solutions**

- 3 antennas: measure closure phase; first antenna-based phase calibration.
- Evaluate baseline-dependent (closure) errors.

#### **5.5.3 First images**

- Simple fields (multiple point sources)
- Self-calibration on bright calibrators; evaluate dynamic range.

#### **5.5.4 Calibrator surveys**

- Survey pre-selected sources from CLASS, SUMSS, ATCA etc. at Band 3 initially; then higher frequencies.
- Develop network of calibrators suitable for fast switching.
- Ditto for phase transfer between frequencies

#### **5.5.5 Initial spectral-line mode tests**

- Limited number of correlator modes (those required for early science)
- Test bandpass calibration
- Check for spectral baseline stability and standing waves

#### **5.5.6 Initial linear polarization tests**

- Measure instrumental polarization for Band 3
- Initial polarization measurements for point sources
- Measure polarized primary beam (at least near sidelobes) and assess stability.

### **5.6 Early Science Array (antennas 1 – 8)**


#### **5.6.1 Phase fluctuations**

- Characterize phase fluctuations (long continuous observations of point sources); compare with site testing interferometer data
- Test instrumental phase stability across the sky
- Characterize decorrelation due to atmosphere
- Measure long-baseline phase structure function
- Correlate phase stability and refractive pointing jitter
- Investigate dry phase fluctuations (i.e. those that do not correlate with WVR)

#### **5.6.2 Fast switching**

Evaluate the fast switching technique using groups of a few closely-separated calibrators.

- Calibrator flux density.
- Calibrator separation
- Atmospheric conditions
- Frequency (initially Band 3; then higher frequencies)
- Switching cycle time, including settling time on source as well as slew time

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- Test atmospheric models

### **5.6.3 WVR phase correction**

Evaluate phase correction on long baselines using bright calibrators.

- Conversion to phase
- Dependence on atmospheric conditions
- Dependence on frequency
- Atmospheric model
- Strategy for combining WVR and fast switching.

### **5.6.4 Instrumental phase transfer between frequencies**

- Test phase transfer between frequencies for fast and slow switching.
- Optimize sampling, cycle time, pattern

### **5.6.5 Optimum data-reduction algorithms**

- Phase interpolation
- Use of WVR data
- Imaging and deconvolution

### **5.6.6 Mosaic tests**

- Optimize sampling grid and pattern
- Optimize sampling speed

### **5.6.7 Optimize on-line blanking and flagging**

- Tracking error
- LO out of lock
- Subreflector, calibration system out of position
- Interference etc.?


### **5.6.8 Operational calibration procedures**

Confirm that all of the calibration procedures work with longer-baseline arrays.

- Temperature and flux-density scales
- Gain
- Bandpass
- Pointing (global and offset)
- Focus, collimation, feed position
- Polarization
- Antenna position/delay
- Primary beam
- Local oscillator coherence

## **6 Science Verification**

The following proposals are based on the equivalent procedures for the VLT, as described in VLT Science Verification Policy and Procedures. There will need to be modifications for ALMA because of the evolving form of the array: the full scientific capabilities of a mode will not be realized until the completion of construction, but a

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mode may first be verified with a small number of antennas. It may be appropriate to repeat science verification of a subset of modes periodically as the array grows, and certainly at the completion of construction. An additional constraint for Early Science will be the need to combine observations in different configurations to obtain adequate uv coverage.

## 6.1 Purpose

The goals of SV are:

- Offer to users first-grade science data from a new mode of ALMA and involve them in prompt scientific exploitation
- Demonstrate the potential of the mode to a wide community
- Foster an early scientific return
- Test pipeline and reduction tools
- Provide feedback to ALMA operations, the CSV team, construction IPT's and ARCs as appropriate

## 6.2 Prerequisites

Each mode should be debugged and verified by the commissioning team before the SV phase, so that the test is expected to succeed. This phase should be terminated by a formal acceptance review. The SV phase is intended to be a complete end-to-end test.

The following prerequisites apply to all bands, continuum and those spectral line modes selected for early science, using appropriate observing modes. Before a mode is released for science verification, it must be fully commissioned and documented, and the array performance must be assessed as meeting the appropriate subset of science requirements, modified appropriately for the number of antennas. Quantitative criteria include:


Image sensitivity in a given integration time

Image fidelity (dynamic range, reproducibility, comparison with results from other arrays)

Astrometric accuracy

Spectral dynamic range

The modes offered for Early Science will be interferometry for single fields and pointed mosaics with at least the correlator modes given in Section 3 (loosely continuum, medium and high spectral resolution) at baselines of up to 4(?) km and with the option of combining total-power data from a single antenna.

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### 6.3 Procedure for Science Verification

The SV plan for a mode is developed by a SV team. This will include but is not limited to members of the core CSV group. They will involve members of the community as appropriate, perhaps via an open call for ideas. The SV team will be responsible for selection of a small number of proposals according to the following criteria:

- Scientific interest
- Pushing the array close to its limit (consistent with technical feasibility at the time)
- Resulting in a complete dataset suitable for prompt exploitation.

On completion of observing (possibly in multiple configurations), data reduction and quality control, the data (raw and reduced, together with scripts and documentation) will be made public.

VLT instruments typically have 6-10 SV proposals. Given the large number of frequency, configuration and correlator mode combinations with ALMA, it is likely that one or two SV proposals per mode would be appropriate.


The duties of the SV team are:

- Development and pre-selection of SV projects
- Preparation of proposals and scheduling blocks using the Phase 1 and 2 observing tools, respectively.
- Maintenance of SV web pages, which should describe the SV plan well in advance of observations and list the data as they become public.
- Reduce and perform quality checks on the data.
- Deliver the data to users on request
- Provide information about and assist users with exploitation of the data.

## 7 Demonstration Science

Demonstration science has been identified as a special case of science verification during which “pretty pictures” with the potential for publicity (as well as scientific impact) are produced. A small number of such projects should be identified as part of the SV process.

These will almost inevitably require use of multiple array configurations, since adequate imaging requires sampling of a large range of spatial scales. Scheduling such observations before the start of Early Science is a concern, as a minimum of 6 antennas will be needed, and the number of array reconfigurations possible in the time available will be limited.

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## 8 Commissioning and Science Verification after Early Science (2007 – 2012)

The process of science verification must continue as the array evolves. In addition, there are many new tasks:

- 8.1 Antenna configurations
  - Up to 64 antennas in all science configurations
  - Procedure for adding a new antenna; use of a test subarray
  - Reconfiguration
  - Subarray management
- 8.2 Bands
  - Additional bands (4, 8, 10)
- 8.3 Correlator modes
  - All continuum modes
  - All spectral-line modes
- 8.4 Polarization
  - Linear
  - Circular
  - High-accuracy linear (QW plate, Band 7)
- 8.5 Pipeline
  - Exercise on full range of frequencies, array configurations, correlator modes, sources,
  - Test and improve pipeline heuristics
- 8.6 Dynamic scheduling
  - Optimization based on observing experience
  - Rules for run-time selection of integration time, calibration strategy, etc. based on conditions.
- 8.7 New observing modes
  - Very large mosaics
  - Combination with ACA and single dish
  - On-the-fly mapping
  - Solar
  - Pulsar
  - VLBI
  - Refined calibration procedures for all modes, deriving a matrix of anticipated accuracies and precisions.
  - Interferometric on-the-fly mapping

## 9 The Commissioning Team



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The commissioning team will be led by a senior scientist, either the Project Scientist or someone reporting directly to him. It will be multidisciplinary, including:

- Technically-qualified astronomers
- Engineers in each of the key areas (IPT or discipline-based), whose primary roles are to act as first point of contact in case of problems and liaison with engineering support.
- Specialised technical support, where this cannot sensibly be provided by Operations.

The commissioning team is likely to consist of a mixture of international staff based in Chile, long-term visitors from Europe or the USA and local staff. The expectation is that there will be both experienced astronomers and engineers and junior staff, the latter being more likely to be seconded from and/or to move to Operations. The involvement of outside astronomers will be carefully managed: there will occasionally be good reason for experienced people to join the commissioning team for shorter periods, but they will always work for the team in some capacity. Under no circumstances will astronomers whose prime motivation is the acquisition of their own observations be supported by the commissioning team.


Support and close collaboration will be required from:

- Operations (array operators; staff seconded to the commissioning team for training; maintenance engineers; IT support; etc.)
- Systems Integration (normally the first contact in case of problems with newly installed equipment).
- Construction IPTs.
- Particularly close collaboration will be required with the Computing IPT, especially for the real-time systems but also for data analysis and with the SSR scientists.

The staffing proposed for ALMA Operations from 2006 includes:

- 1 Science Programme Manager
- 2 Duty Astronomers
- 2 ALMA Fellows
- 3 Systems Astronomers

with an additional 4 Duty Astronomers to be hired in 2007. Before the start of Early Science, the primary duties of these staff will be commissioning and science verification. The expectation in full-time operation is that these staff will divide their time between OSF and Santiago on a “turno” system, but a more flexible schedule would be appropriate during commissioning, especially in the early stages.

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The proposed staffing level for the CSV team for the period from the arrival of the first antenna at the AOS to the start of early science is:

Project Scientist  
4 Science IPT (0.75)  
4 external specialists (average 0.25)

in addition to the Operations component.

## 10 Schedule

The list of commissioning tasks (Section 5) is now reasonably complete. The next step is to expand each of the items into a Task Data Sheet following the example of the VLT Commissioning Plan. In practice, many of the tests can be carried out in parallel; others require repetition at regular time intervals or under a range of conditions. An indicative draft schedule will be produced once the timescale for systems integration in Chile is defined, with the understanding that it will require frequent updates.